Integrated Computational Materials Engineering (ICME) Development of Carbon Fiber Composites for Lightweight Vehicles

Dr. Xuming Su (PI)

Dr. David Wagner (Co-PI)

Ford Motor Company

June 11, 2019

Project ID: MAT101

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project Overview

Timeline

- Project start date: Oct. 1, 2014
- Project end date: Dec. 30, 2018
- Percent complete: **100%** Complete

Budget

- Total project funding
  - DOE share: $6,000,000
  - Contractor share: $2,580,000
- FY2018 project funding
  - DOE share: **$1,893,628** (this completes the project) (Any proposed future work is subject to change based on funding levels)
  - Contractor share: $820,250

Barriers

- Predictive modeling tools
  - ICME models for Carbon Fiber Reinforced Polymer composites (CFRP)
  - Error of model predictions vs tests ≤15%
    - Manufacturing process models
    - Vehicle performance models
- Performance
  - Achieving ≥25% weight reduction
  - Meet packaging, safety and durability requirements of vehicle structural members
- Cost
  - Cost increase ≤$4.27/lb. of weight saved

Partners

- Ford Motor Company (Lead)
- Dow Chemical
- Northwestern University
- NIST/University of Maryland

Relevance and Project Objective

- <u>Overall Objectives</u>
  1. Develop **predictive** Integrated Computational Materials Engineering (ICME) **modeling tools**
     - Simulate the manufacturing process effects on material properties
     - Predict part and assembly attributes (safety, durability, strength and NVH)
       - Material models based on material design and manufacturing processes
       - CAE analysis accounting for local material variations due to process influences
     - Error of model predictions vs experimental measurements ≤15%
  2. Design and optimize a carbon fiber front subframe for a five passenger sedan using ICME models developed (CAE only, no prototypes or vehicle tests)
     - **Meet packaging, NVH, safety and durability requirements**
     - Capable of achieving **≥ 25% weight reduction**
     - **Cost penalty ≤ $4.27 / lb. of weight saved**
- <u>Impact / Relevance to DOE</u>
  - Speed up the application of CFRP in vehicle structures for lightweighting to address the DOE 2030 targets
  - Improve CAE prediction capability to achieve the most efficient design of lightweight, high quality CFRP vehicle structures at lowest cost

Milestones

Milestone	Date	Status	Type
Test matrix and plan finalized	12/31/2014	Completed	Technical
Database structure established	3/31/2015	Completed	Technical
Validation part molding plan established	6/31/2015	Completed	Technical
Resin and carbon fiber characterization completed	12/30/2015	Completed	Technical
Resin and carbon fiber properties meet performance requirement	**12/30/2015**	Completed	**Go**/No-Go
Plaque Molding Completed	6/30/2016	Completed	Technical
Preform/draping model correlated	6/31/2016	Completed	Technical
Fiber interfacial properties completed	9/30/2016	Completed	Technical
The framework for linkage of ICME models accomplished	**12/30/2016**	Completed	**Go**/No-Go

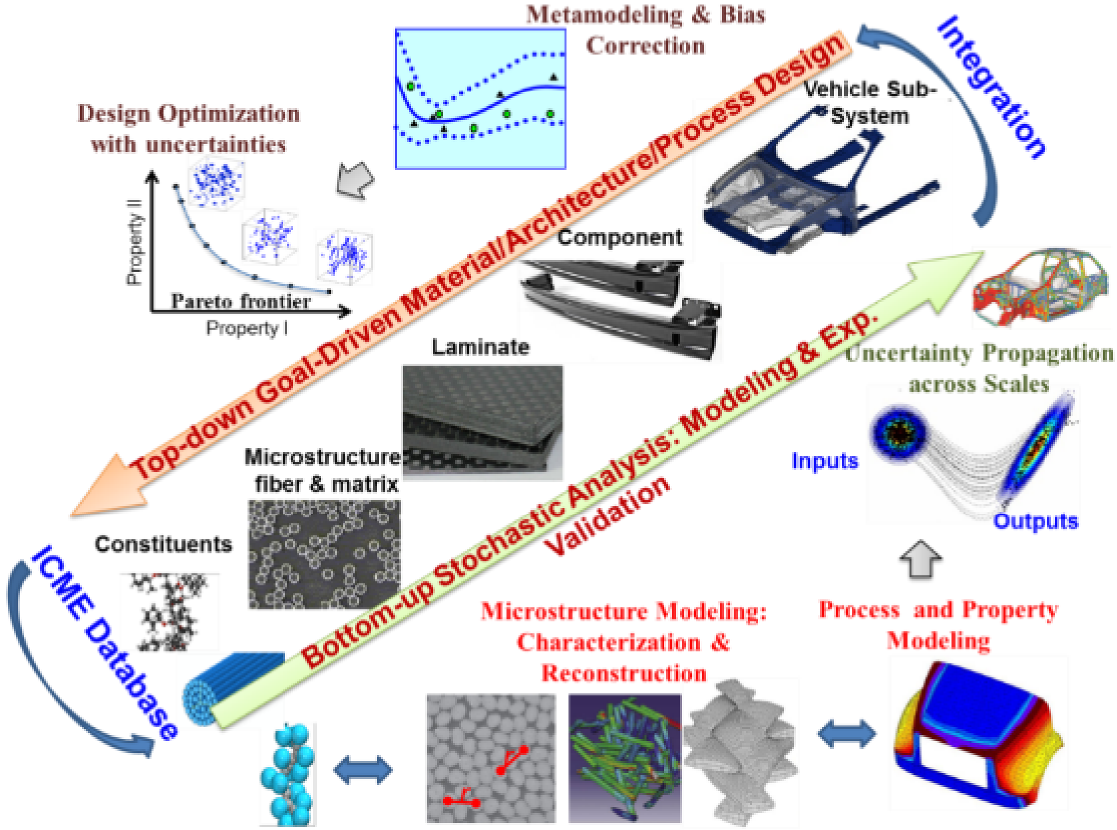
Milestones

Milestone	Date	Status	Type
Fracture and fatigue model established	~~3/30/2017~~ 12/31/2017	Completed	Technical
ICME model integration completed and validated	6/30/2017	Completed	Technical
Model accuracies meet specified targets	~~9/30/2017~~ 12/31/2017	Completed	Technical
Integrated ICME model meets accuracy targets	12/31/2017	**Completed** for Top Hat	**Go**/No-Go
	6/29/2018	Completed for Subframe	**Go**/No-Go
Subframe Design Concepts Developed	3/30/2018	Completed	Technical
ICME Model Reliability, Robustness and Efficiency Assessed	6/30/2018	Completed	Technical
Design Optimization Completed; Performance, Weight and Cost	9/30/2018	Completed	Technical
Project Summary and Reports	**12/31/2018**	**Completed**	**Project End**

Any proposed future work is subject to change based on funding levels

Approach / Strategy

- Develop predictive tools using Integrated Computational Material Engineering
  - Top-down goal-driven design & optimization
  - Bottom-up multi-physics, multi-scale modeling
  - Integration of models of materials, processes, structural performances, and cost
- Apply ICME tools to achieve the most efficient design of lightweight, high quality CFRP vehicle structure with low cost



Approach: Four Tasks for ICME

Task 1: Material Characterization and ICME Database

- Testing and characterization of resin, carbon fiber and selected composite materials.

Task 2: ICME Model Development and Validation

- Develop and validate predictive computational models for Carbon-Fiber Reinforced Polymer (CFRP) composites needed for ICME workflow

Task 3: ICME Model Integration and Validation

- Integrated Models developed in Task 2 into commercial software
- Develop full ICME workflow in multi disciplinary optimization

Task 4: ICME-Based Design and Optimization

- Demonstrate ICME multi disciplinary optimization on carbon fiber composite intensive subframe design.

Technical Metrics & Results

Table 1: Minimum Modeling Elements by Manufacturing Phase

Model	Manufacturing Phase	Modeled Element	TARGET Percent Error Compared to Experimental	ACTUAL Percent Error Compared to Experimental
Constituent Material (fiber / interphase / resin and assembly of such)	N/A	Robust, accurate and reliable constitutive models for each constituent material as well as the composite assembly under expected service conditions including high-strain rates utilizing physics based model	≤ 15%	≤ 15% (some crash modes have higher error)
Part Properties	During and After Molding	Microstructure morphology	N/A	
		Optimized cycle time, and local thickness, fiber length and orientation of the final part	≤ 15%	≤ 15%
Assembly Properties	After Joining and Assembly	Load to failure, failure location, and failure mode, stiffness/deflection, dynamic performance, energy absorption/crashworthiness	≤ 15%	≤ 15%

Table 2: Subframe Design

Weight	Compare to steel subframe for the same performances	**TARGET** > 25% save	**Multi-material with Steel Intensive 30% save**	Multi-material with CF-SMC Intensive 41% save
Cost	Compare to steel design for the same performances	**TARGET** ≤ $4.27 per pound weight saved	**Multi-material with Steel Intensive $4.01 / lb.-saved**	Multi-material with CF-SMC Intensive $8.90 / lb.-saved

Accomplishments Task 1: Material Testing Overview

Item	Description	Deliverables
Subtask 1.1	Characterize resin behavior from viscous semi-liquid form to the cured form	• Characterized mechanical properties of the fully cured neat resin to inform continuum, fracture and fatigue models • Provided characterization of uncured material to support preforming and molding simulation
Subtask 1.2	Measure mechanical properties of carbon reinforcing fibers and fabric	• Measured mechanical properties of the fiber constituent to supplement published values made available by DowAKSA • Characterized the uncured prepreg to inform preforming and molding simulations
Subtask 1.3	Measure interphase property at quasi-static loading condition	• Characterized mechanical properties of composite coupons as they relate to the fiber/matrix interface • Enabled correlation of microstructure-based models to determine interphase qualities
Subtask 1.4	Characterize CFRP coupons at quasi-static and high strain rates, low- and high-cycle fatigue tests	• Produced CFRP plaques for characterization • Characterized CFRP coupons under monotonic conditions at quasi-static and elevated strain rates, and at ambient and elevated temperatures as input and validation for continuum, fracture and fatigue models • Conducted low- and high-cycle fatigue tests to provide input for fatigue models
Subtask 1.5	Create the ICME database for CFRP	• Delivered data and analysis of mechanical characterization results to the public

Task 1: Over 100 Datasets for Public Release

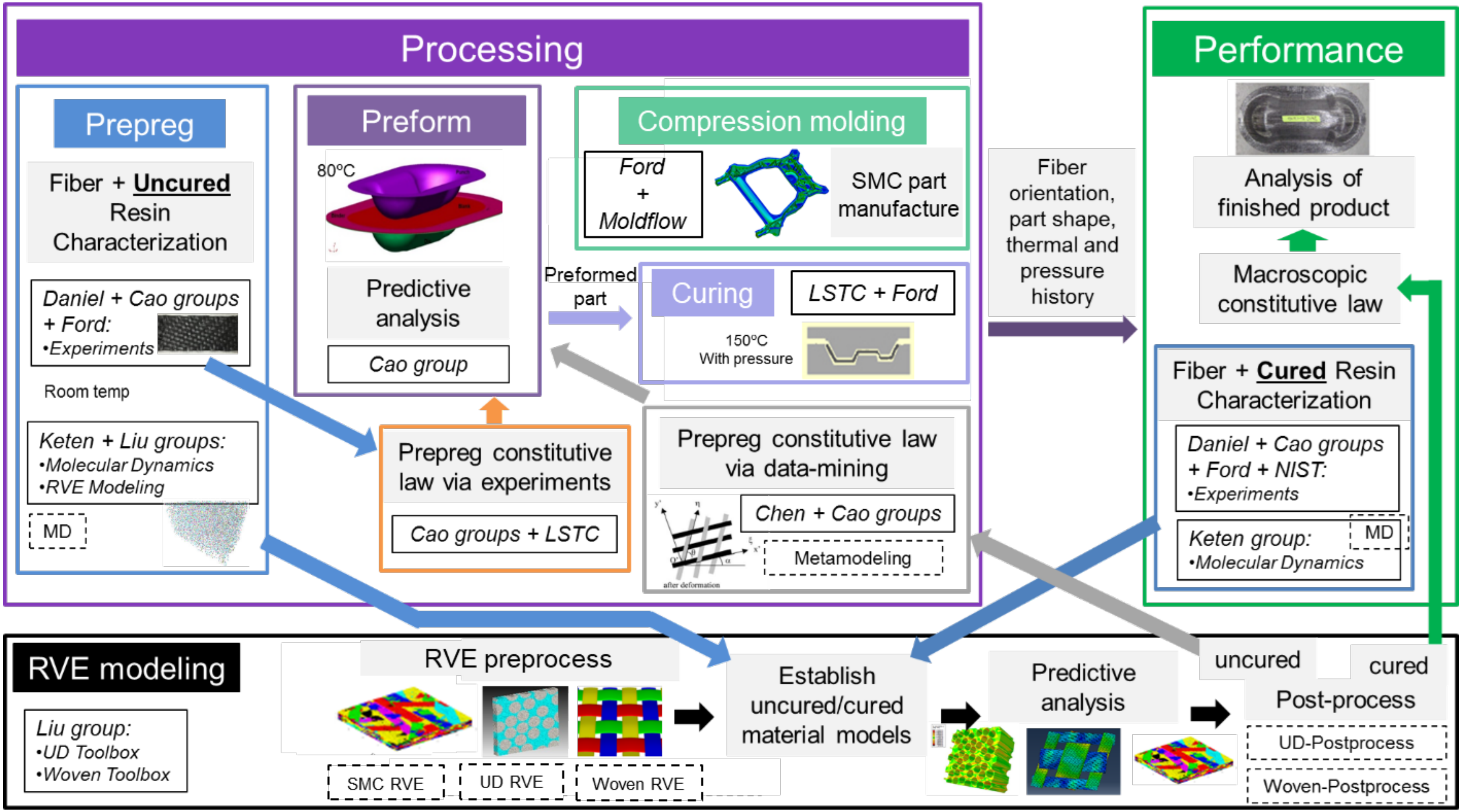
	Test	Properties
Long UD (50%)	Tension 0° (QS, ER, ET)	E_1, ν_{12}, F_{1t} , ε_{1t}^u
	Tension 90° (QS, ER)	E_2, F_{2t}, ε_{2t}^u
	Tension 10° (QS)	G_{12}, F_{12}, γ_{12}^u
	Compression 0° (QS, ER)	E_1, F_{1c}, ε_{1c}^u
	Compression 90° (QS, ER)	E_2, F_{2c}, ε_{2c}^u
	Coupon in torsion (QS)	G_{13}, G_{23}
	Short sandwich beam (QS)	F_{23}
	Double cantilevered tapered (QS)	G_{Ic}
	Edge notched flexure (QS)	G_{IIc}
Long UD (45%)	Tension 0° (QS, ER)	E_1, ν_{12}, F_{1t}
	Tension 90° (QS, ER)	E_2, F_{2t}
	Tension 10° (QS)	G_{12}, F_{12}, γ_{12}^u
Long UD (55%)	Tension 0° (QS, ER)	E_1, ν_{12}, F_{1t}
	Tension 90° (QS, ER, ET)	E_2, F_{2t}
	Tension 10° (QS)	G_{12}, F_{12}, γ_{12}^u
Chopped (50%)	Tension 0° (QS)	E_1, ν_{12}, F_{1t} , ε_{1t}^u
	Tension 90° (QS)	E_2, ν_{21}, F_{2t} , ε_{2t}^u
	Compression 0° (QS)	E_1, F_{1c}, ε_{1c}^u
	Compression 90° (QS)	E_2, F_{2c}, ε_{2c}^u
	Iosipescu shear (QS)	G_{12}

	Test	Properties
Twill 660gsm	Tension 0° (QS, ER)	E_1, ν_{12}, F_{1t} , ε_{1t}^u
	Tension 45° (QS)	G_{12}, F_{12}, γ_{12}^u
	Compression 0° (QS)	E_1, F_{1c}
	Coupon in torsion (QS)	G_{13}, G_{23}
	Short beam in bending (QS)	F_{13}
	Double cantilevered tapered (QS)	G_{Ic}
Twill 400 gsm	Tension 0° (QS)	E_1, ν_{12}, F_{1t} , ε_{1t}^u
	Tension 45° (QS)	G_{12}, F_{12}, γ_{12}^u
	Tension 90° (QS)	E_2, ν_{21}, F_{2t} , ε_{2t}^u
	Compression 0° (QS)	E_1, F_{1c}, ε_{1c}^u
	Compression 90° (QS)	E_2, F_{2c}, ε_{2c}^u
Plain 660gsm	Tension 0° (QS)	E_1, ν_{12}, F_{1t} , ε_{1t}^u
	Tension 45° (QS)	G_{12}, F_{12}, γ_{12}^u
	Tension 90° (QS)	E_2, ν_{21}, F_{2t} , ε_{2t}^u
	Compression 0° (QS)	E_1, F_{1c}, ε_{1c}^u
	Compression 90° (QS)	E_2, F_{2c}, ε_{2c}^u
NCF	Tension 0° (QS)	E_y, ν_{yx}, F_{yt}
	Tension 45° (QS)	G_{xy}, F_{xy}
	Coupon in torsion (QS)	G_{xz}, G_{yz}

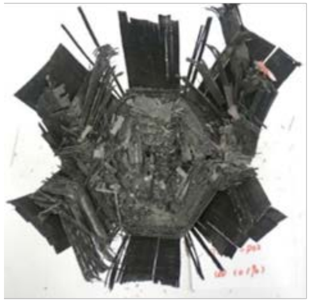
	Test	Properties
Uncured Charges	Differential scanning calorimetry	m, n, A, B, T_a, T_b, ΔH
	Reactive viscosity	α_g, c_1, c_2, B, T_b, n, τ
	PVT	b_1, b_2, b_3, b_4, ζ, C
	Heat capacity	c
	Thermal conductivity	λ
Cured Resin	Uniaxial tension (QS, ER, ET)	E, ν, F_t, ε_t^u
	Uniaxial compression (QS, ER)	E, F_c, ε_c^u (at yield)
	Thin-wall cylinder in torsion (QS)	G, F_s, γ_s^u
	Notched beam in bending (QS)	G_{Ic}
Individual Fibers	Single-fiber tensile	E, F_t, ε_t^u

	Test	Properties
Twill 660gsm prepreg	Tensile (QS, ET)	E_t, ε_u
	Bias extension (QS, ET)	G(d)
	Self-loaded bending (ET)	E_c
	Surface interaction (QS, ER, ET)	Interaction factor
NCF prepreg	Tensile (QS, ET)	E_t, ε_u
	Bias extension (QS, ET)	G(d)
	Self-loaded bending (ET)	E_c
	Surface interaction (QS, ER, ET)	Interaction factor

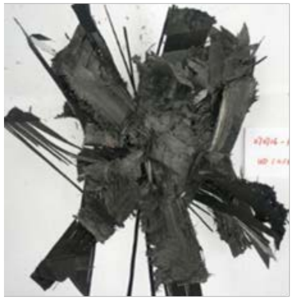
Task 2: Multiscale Integrated Modeling Flowchart



Task 2: Component Crash Model Validation

Testing	Simulation
	

UD 0/90

Testing	Simulation
	

UD +60/0/-60

Validation summary VMM project DE-EE-0005661

Crash mode	Software A	Software B	Software C		Software D		Software E
			Supplier 1	Supplier 2	Supplier 1	Supplier 2	
NCAP	62	35	86	49	80	60	37
IIHS	67	6	83	55	65	26	46
Angular	31	7	30	57	61	29	35
Pole	37	58	70	66	42	5	31
LS center	34	55	35	70	40	31	38
LS Quarter	65	7	75	73	78	38	64
Average	49	28	63	61	61	31	42

Comparison of Test to CAE via CORA from C. Gehre, H. Gades, and P. Wenicke, "Objective Rating Of Signals Using Test And Simulation Responses", Proc. Int. Tech. Conf. Enhanced Safety Vehicles, 2009.

Validation summary in this project

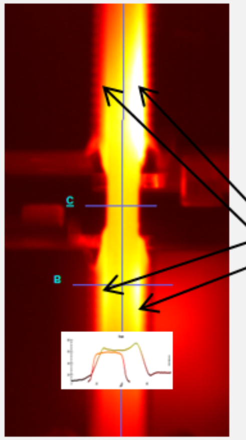
UD 0-60		Exp(CoV%)	Sim	Error
Axial crushing	Energy(J)	2274.1(8.6)	2380	4.70%
(v=4.4m/s)	Load(KN)	52.3(8.0)	53.8	2.80%
Dynamic 3-point bending	Peak L(N)	10063.1(0.5)	8460.1	16.00%
(v=4.67m/s)	Dis(mm)	11.7(4.6)	12.6	7.30%
UD 0-90		**Exp(CoV%)**	**Sim**	**error**
Axial crushing	Energy(J)	3392.3(14.3)	2150	36.70%
(v=4.4m/s)	Load(KN)	76.1(22.5)	42.5	44.20%
Dynamic 3-point bending (v=4.85m/s)	Peak L(N)	9048.2(7.9)	8690.2	3.90%
	Dis(mm)	11.5(3.0)	12.4	8.30%

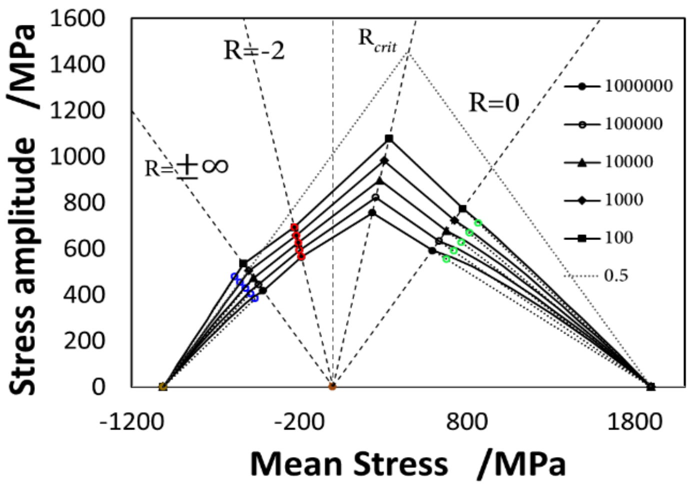
The prediction accuracy on various scenarios in crash simulation is greatly improved

Accomplishment Task 2: Fatigue Analysis

- Implemented a new module for fatigue life prediction of continuous fiber reinforced composite in **nCode**
- Developed fatigue test and characterization procedure for carbon composites
- Completed over 500 tests to define fatigue behaviors of the materials studied (UD, Woven, SMC).
- Validated applicability of linear damage summation (Miner's rule)

Temperature Evaluation during Fatigue Testing

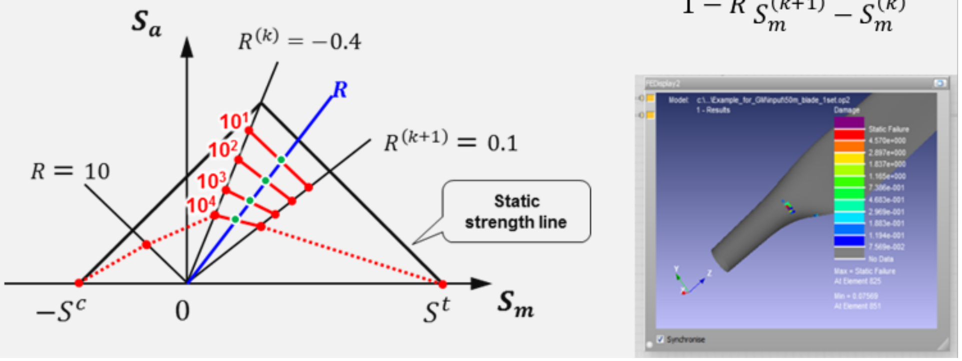




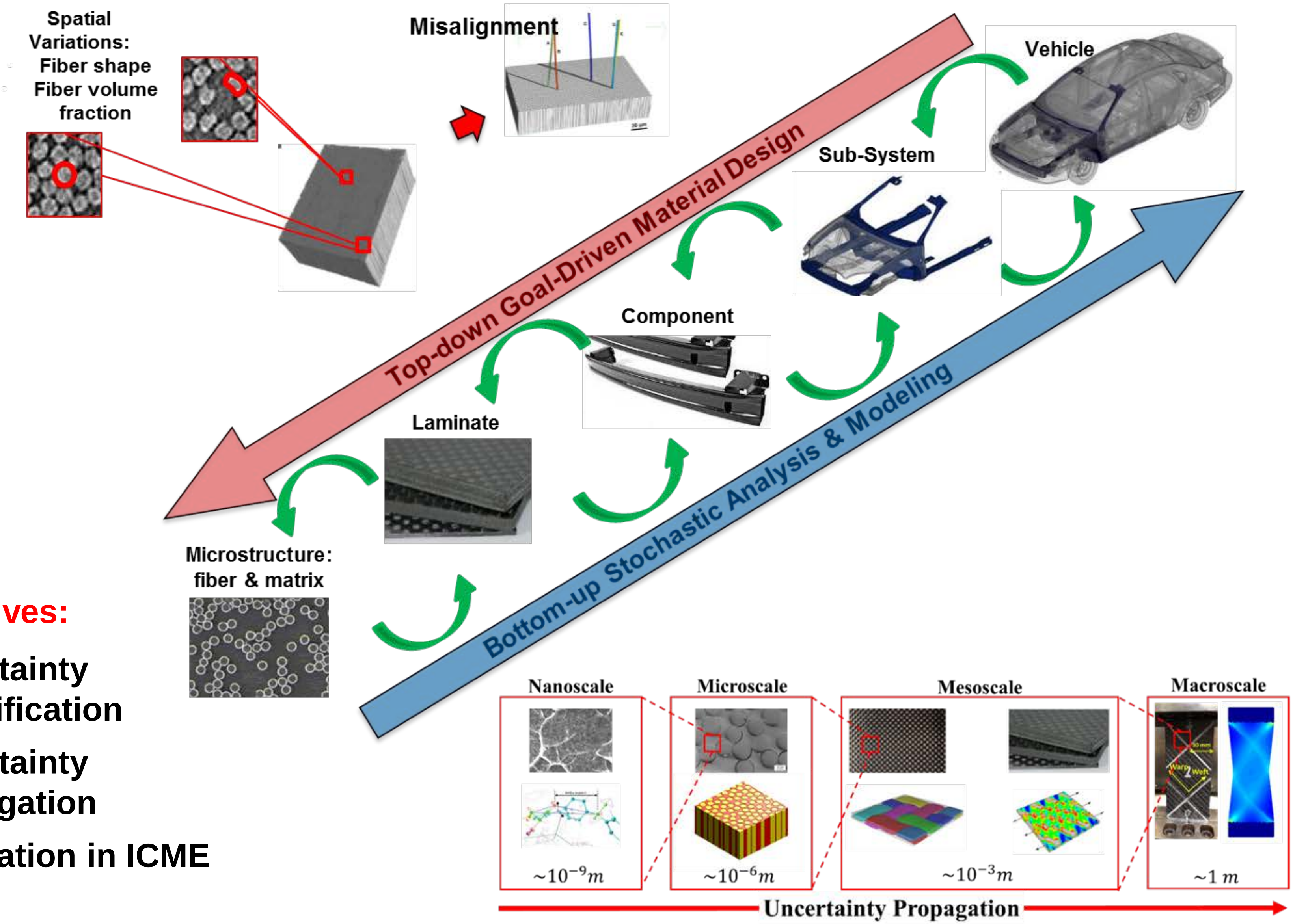
Constant fatigue life diagrams (CFLDs) for UD at 0°

nCode Fatigue Failure Criteria (FFC) for Composites (plane stress at ply-level)

$$S_a^R(N_f) = \frac{S_a^{(k)} - \dfrac{S_a^{(k+1)} - S_a^{(k)}}{S_m^{(k+1)} - S_m^{(k)}} S_m^{(k)}}{1 - \dfrac{1+R}{1-R}\dfrac{S_a^{(k+1)} - S_a^{(k)}}{S_m^{(k+1)} - S_m^{(k)}}}$$



Task 2: Microstructure Variations in Multiscale CFRP



Objectives:

- Uncertainty quantification
- Uncertainty propagation
- Integration in ICME

Accomplishment Task 2: Summary

- Completed the Task 2: Model Development and Model-level Validation Report
- All the models meet the FOA accuracy target based on the validation tests conducted

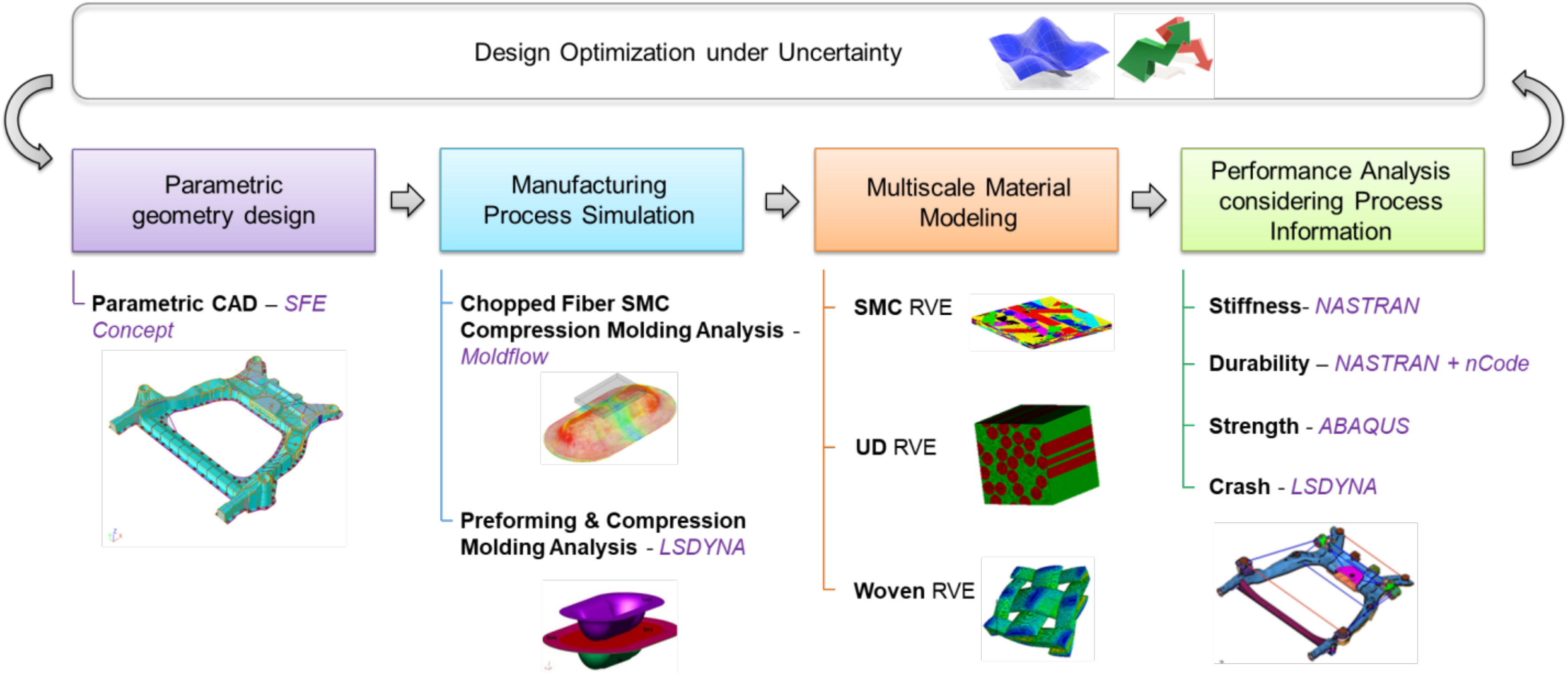
Evaluation Metrics					
Manufacturing Phase		**Experimental Baseline**	**Modeled Element**	**This Project**	**FOA Target**
Manufacturing process simulation	Preforming	Woven double dome	Draw in	< 14%	⩽ 15%
			Yarn angle	< 10%	
	Compression molding	SMC 12x18 plaque	Filling time	< 11.5%	
			Fiber orientation	< 10%	
RVE model prediction of CFRP	UD	UD coupon	Elastic constant	< 10%	
			Failure strength	< 10%	
	Woven	Woven coupon	Elastic constant	< 10%	
			Failure strength	< 13%	
	SMC	SMC coupon	Elastic constant	< 6%	
			Failure strength	< 12%	
Structural performance simulation	Crash	UD hat section	Energy absorption	< 10% for -60/0/60 ~40% for 0/90*	
		Woven hat section	Energy absorption	< 10%	
	Fatigue	UD laminates	Fatigue limit	< 11%	

*** Large variations in testing data at UD axial**

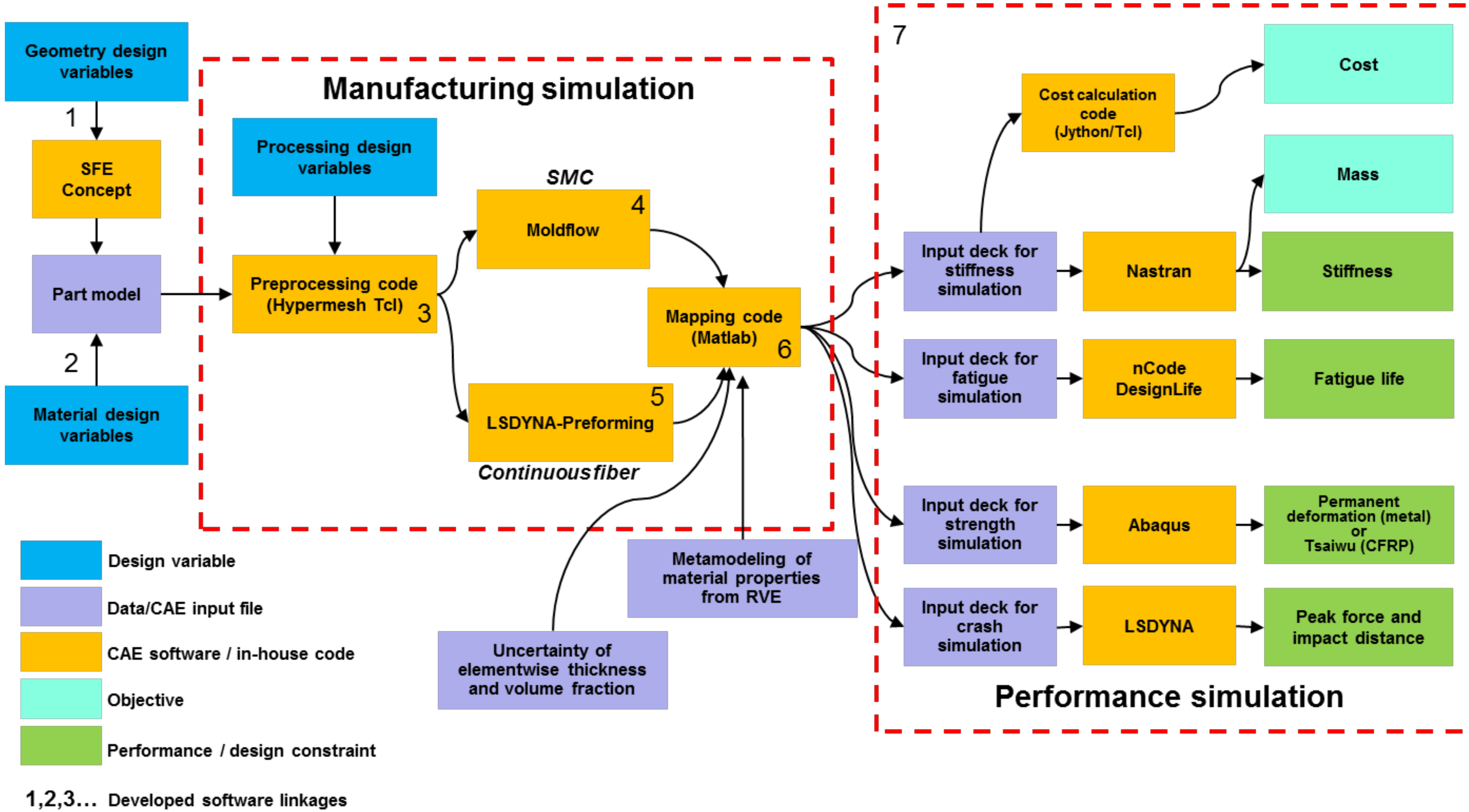
Accomplishment Task 3: Model Integration and Validation

The integrated ICME workflow contains the following key features:

- Process integration and automation
- Parametric geometry design module
- Manufacturing process simulation module
- Multiscale material modeling module
- Attribute simulations
- Optimization and Design-of-Experiment capability



Task 3: Full ICME Workflow

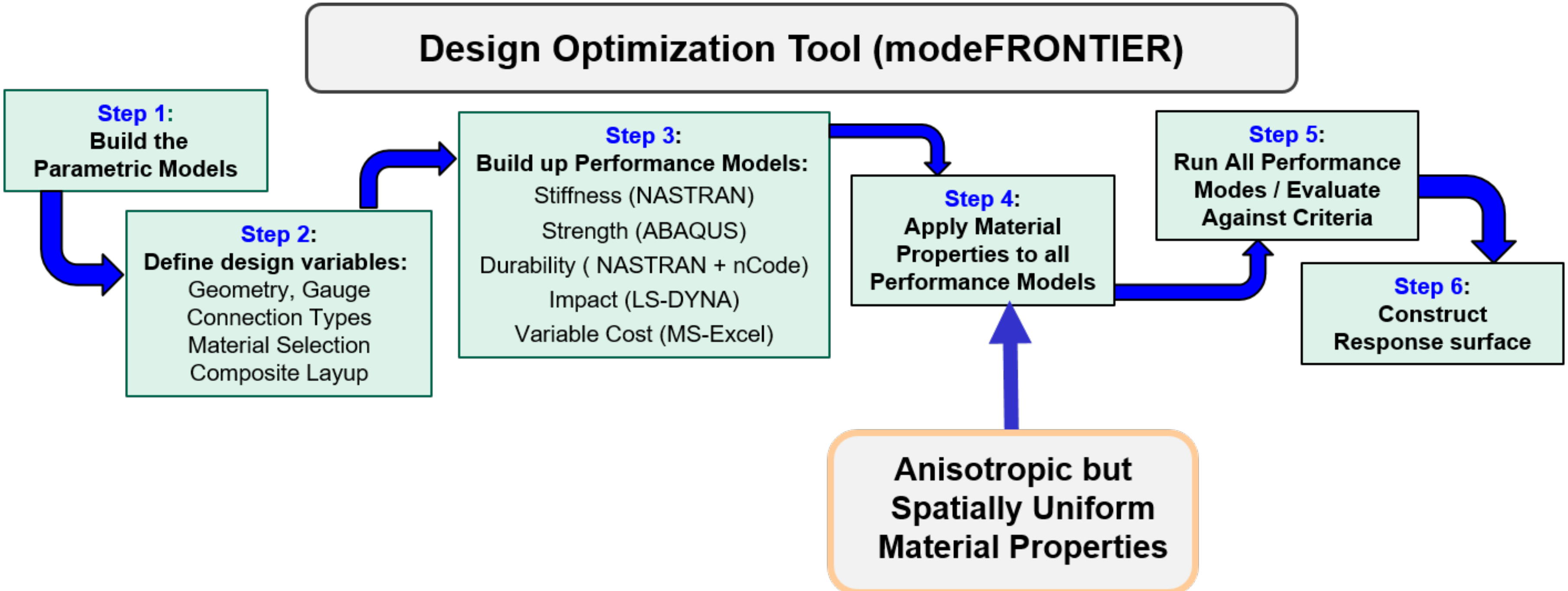


Ford's High Performance Computing Run Times

Example: SMC Intensive Subframe
all analyses are COMPONENT (not full vehicle)

	Average Run Time
Parametric CAD (SFE) …………………………………..	3 ~ 4 min
Composite layup generator (Jython scripts) ………….	< 1 min
FEA Model Preprocessing (Jython scripts)	~ 2 min
Stiffness (NASTRAN) …………………………………….	3 ~ 4 min
Durability (NASTRAN + nCode) ………………………...	~ 1 hour
Strength (ABAQUS) ……………………………………….	20 ~ 30 min
Impact (LS-DYNA) …………………………….…………..	2 ~ 3 hour
Variable Cost (MS-Excel / Jython scripts) ……………..	~ 2 min
1 DOE point after parallelization of attribute simulation	**~ 1 hour (with parallelization)**
NOTE: Compression Molding Simulation ………………	**~ 90 hours**

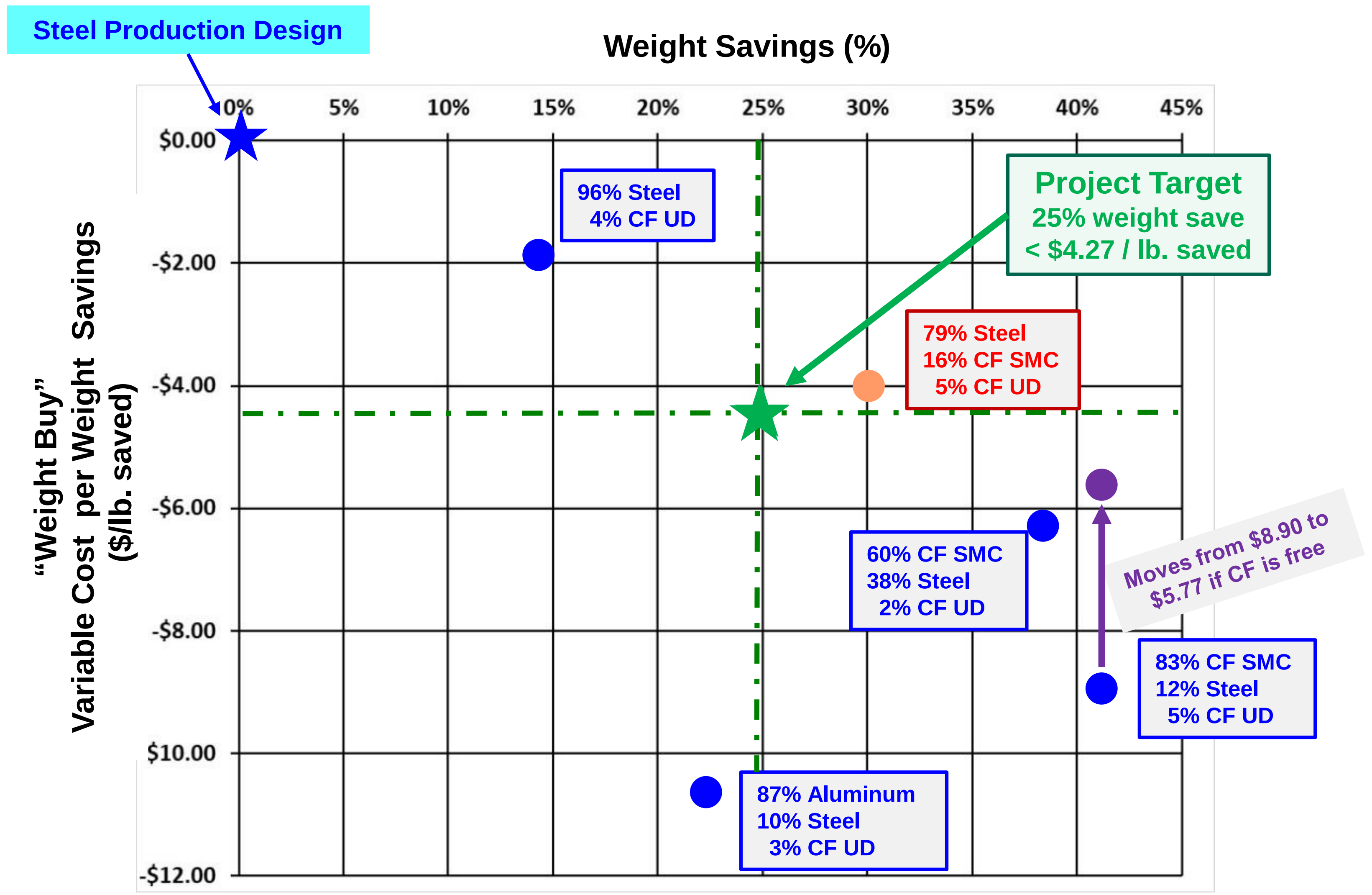
Task 4: ICME-Based Design Optimization



- Used **truncated** process**, without Compression Molding Simulation,** for MDO to accelerate optimization.
- Performance models used anisotropic but spatially uniform material properties during screening runs to find designs that met all performance requirements at reasonable costs.
- Completed 100~150 analyses per day for over three months

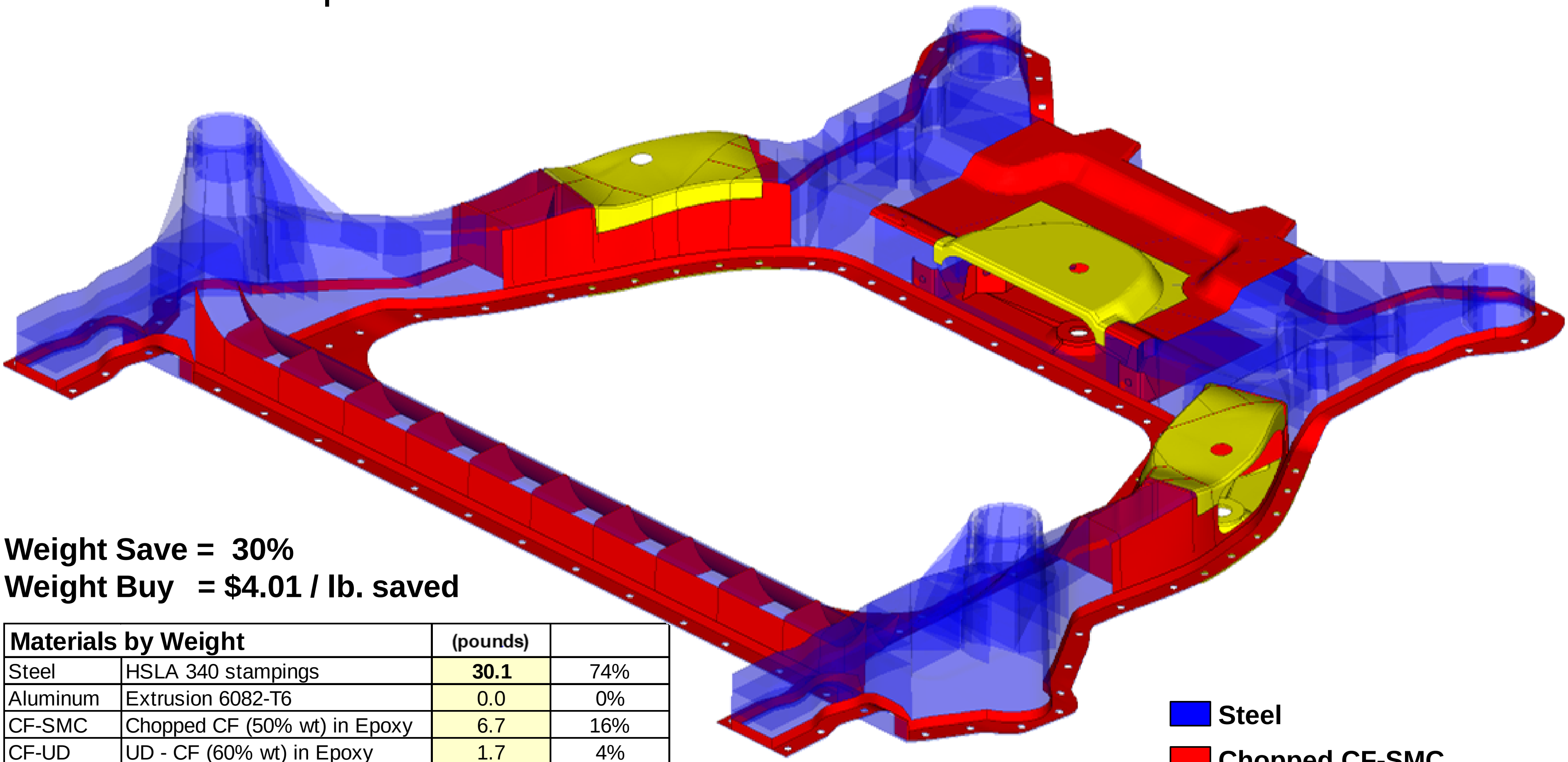
Task 4: Subframe Design

- Performed approximately 10,000 design iterations using the truncated MDO process to find a few interesting designs.



Task 4: Design that Meets Targets

- Multi Material Steel Intensive design with five CF-SMC parts and six CF-UD patches for local reinforcements

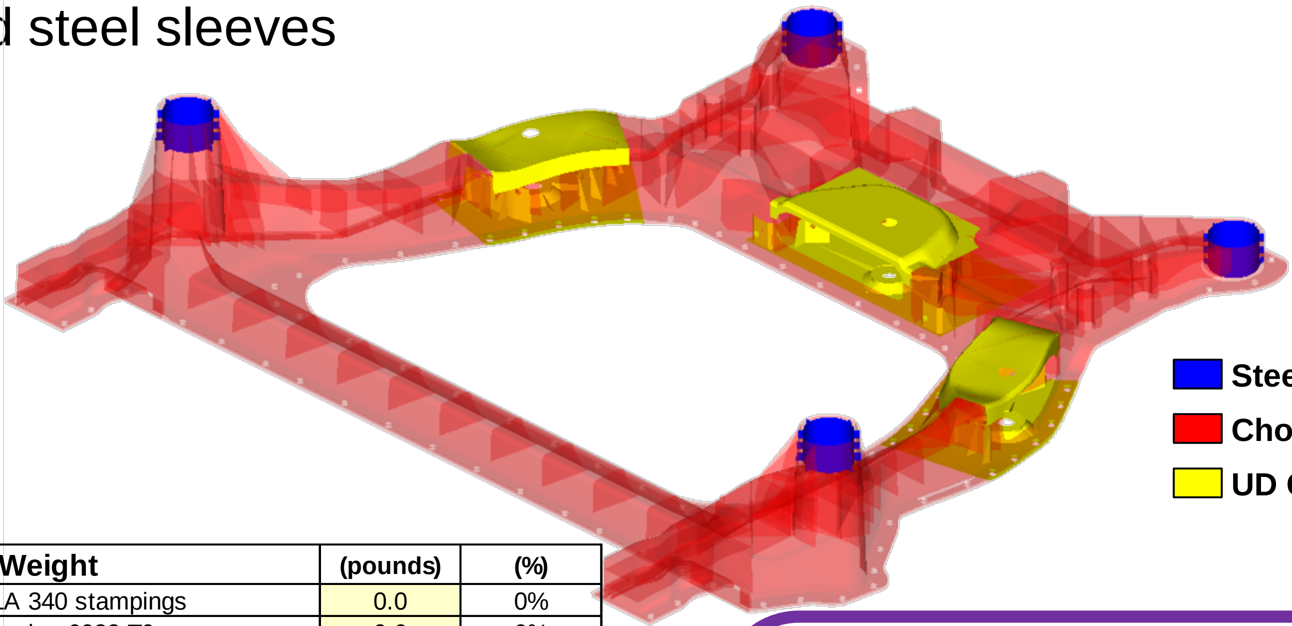


Weight Save = 30%
Weight Buy = $4.01 / lb. saved

Materials by Weight		(pounds)	
Steel	HSLA 340 stampings	**30.1**	74%
Aluminum	Extrusion 6082-T6	0.0	0%
CF-SMC	Chopped CF (50% wt) in Epoxy	6.7	16%
CF-UD	UD - CF (60% wt) in Epoxy	1.7	4%
Adhesive	Structural Epoxy	0.1	0%
Steel	Cold Roll 180	**2.1**	5%
	Total Weight	**40.7**	
Cost	**Variable Cost (Estimated)**	**$170**	

Task 4: Lightest Design SMC-Intensive Subframe

- The lightest design that meets performance (except cost) is a multi material combination of chopped CF-SMC with CF-UD patches and steel sleeves



Materials by Weight		(pounds)	(%)
Steel	HSLA 340 stampings	0.0	0%
Aluminum	Extrusion 6082-T6	0.0	0%
CF-SMC	Chopped CF (50% wt) in Epoxy	**28.2**	83%
CF-UD	UD - CF (60% wt) in Epoxy	1.7	5%
Adhesive	Structural Epoxy	0.1	0%
Steel	Cold Roll 180	4.2	12%
	Total Weight	**34.2**	
Cost	**Variable Cost (Estimated)**	**$313**	

Weight Save = 41%
Weight Buy = $8.90 / lb. saved

To meet Cost Target of $4.27/pound saved,
This design would need to cost $202.
Currently this design has 14.1 + 0.9 = 15.0 pounds CF

Sensitivity to CF Cost	
Carbon Fiber Cost ($/lb)	**Weight Buy Design 1 ($/lb saved)**
$5.00	$8.90
$4.00	$8.27
$2.00	$7.02
$0.01	$5.77

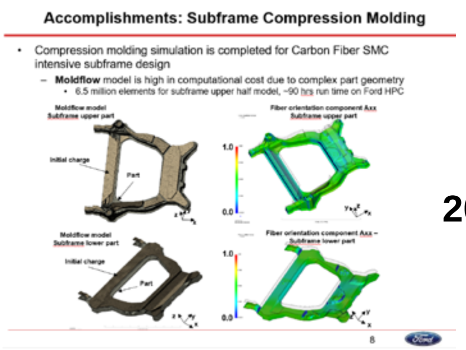
above target of $4.27

Responses to Previous Year Reviewers’ Comments

Approach

Reviewer Comment: The reviewer remarked that Moldflow was used at a small plaque level, which cannot be extrapolated to large 3D parts.

Project Team Response: The team has successfully applied the compression molding simulation module in Moldflow to model the compression molding of a complex subframe with 6.5 million tetra elements. The results reported on slide 8 from 2018 AMR and slide 12 from 2017 AMR offer the status. Yet, it is a concern that Moldflow prediction was not examined in a large 3D part as no prototype was built for such comparison in this project.



2018

Accomplishments

Reviewer Question: How was the uncertainty propagation connected between modeling steps and how did uncertainty influence each successive step?

Project Team Response: A random field of uncertainty sources are created using a top-down sampling approach and mapped to the model at a higher scale level in which spatially varying material properties are determined by a metamodel. The metamodel, in which material response is predicted based on the random field of the uncertainty sources, is created based on the multiscale RVE simulations for the corresponding CFRP material. Thus, in the model at the higher scale level, the material property is a random field as a function of uncertainty sources at a lower scale, instead of a constant.

Reviewer Question: How could the constant life diagrams of the UD laminates (0^o and 90^o) be extended to become a predictive tool for a generalized off-axis laminate composite?

Project Team Response: If we normalize the maximum fatigue stress (σ_{max}) in a CFL diagram with respect to the static tensile strength for $0^o < \theta \leq 90^o$ laminates, the fatigue data for all off-axis angles eventually fall on a single S-N relationship. This single S-N relationship for all off-axis angles, therefore, can be predicted using known fatigue data of 90^o UD laminate alone.

Future Research

Reviewer Question: What subsystem and crash environment is planned for the simulation, and asked if this is planned to be accomplished on a previously tested part to compare analysis with a physical test?

Project Team Response: The front subframe as a component has been analyzed for frontal 90^o rigid barrier crash (see slide 16 in 2018 AMR) using LS-DYNA. Since no prototype builds were part of this project, there is no comparison between the subframe crash prediction and a physical test. The component top hat bending and axial crush predictions to test comparisons were shown on slide 10 in 2018 AMR.

Partners, Collaborators and Coordination

Partner	Weekly	Biweekly	Quarterly
	Meeting Cadence		
Ford Motor Company: automobile manufacturer, composite characterization, process simulation, subframe design and performance analysis, uncertainty and optimization	X	X	X
DOW Chemical: material manufacturer, material preparation, resin and composite characterization, compression molding simulation	as needed	X	X
Northwestern University (five professors and their students): resin and composite characterization, MDA, non-orthogonal model for preforming, RVE, uncertainty and optimization	X	X	X
NIST/University of Maryland: resin and composite characterization, DSpace materials database management	as needed	X	X
CAE software development, model development and implementation, Moldflow, LS-DYNA, nCode, modeFRONTIER	as needed	X	X

Software Tech Transfer

LSTC model implementation in LS-DYNA

New Material Models:

MAT_293_COMPRF
for carbon fiber prepreg forming simulation, released 2nd quarter 2017.

MAT_278_CF_MICROMECHANICS
for carbon fiber prepreg forming simulation, released 1st quarter 2017

Material Model Improvements:

MAT_277 ADHESIVE_CURING_VISCOELASTIC,
material model for resin curing processing, released 2nd quarter 2016.

MAT_054 ENHANCED_COMPOSITE_DAMAGE,
material model for carbon fiber crash simulation, released 1st quarter 2018.

New Features:

Mapping Interface program for utilizing molding simulation result from Moldflow and MoldEx3D for crash simulation released in LS-Prepost in 1st quarter 2018

New LS-DYNA keyword *DEFINE_LAYER for automating the prepreg forming model setup, released in 4th quarter 2017

Moldflow (software from Autodesk)

SMC Compression Molding Improvements in 2018 Moldflow version:

Flexible charge placement, Improved solution stability for complex part designs, New switch over to press force controlled filling

nCode (software from HBM Prenscia)

Composite fatigue prediction module for continuous carbon fiber composites

Remaining Challenges and Barriers – Lessons Learned

- Design Of Experiments throughput limited by computational resources:
  - Availability of commercial software licenses
    - Moldflow only four, SFE only fourteen, on Ford HPC
  - Efficiency of simulation
    - Moldflow simulation is time consuming, only runs on 16 CPUs on Ford HPC
- Improvements needed for geometry and architecture morphing and linkage to Moldflow for compression molding simulation
- Architecture and geometry improvements needed for getting from the design space through topology to high quality meshes for manufacturing and performance simulations.
- Mapping design information to Cost Model needs improvements, currently mass based, need parts, joining, surface treatments, etc.
- With the current cost structure, Woven CFRP of little value, more expensive, with lower strength and stiffness than UD / NCF
- **ICME-based MDO is valuable for initial design investigations !**

Project Summary

- **CF ICME is an exciting project**
  - Speed up the application of CFRP in vehicle structures for light weight
  - Improve the CAE prediction capability, design optimization both in performance and processes, achieving most efficient usage of material, with high quality and low cost
- **ICME is an advanced predictive CAE tool**
  - Based on experimental data and basic physics, robust and accurate
  - Link material science, process simulation and performance analysis
  - Optimize design and manufacturing process to improve quality and reduce cost
- **Accomplishments**
  - NIST database, Fatigue Modeling, Crash Modeling,
  - ICME-based MDO with variable cost estimate, initial subframe designs,
  - Too many others to list here
- **Reflection:**
  - More work is needed …
  - Geometry and architecture to meshes for simulation in batch process
  - Compression molding simulation